LLNL-PRES-838269

ASD Scorpius

Particle-in-Cell Simulations of High Current Density Electron Beams in the Scorpius Linear Induction Accelerator

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August 9, 2022

Presented to the North American Particle Accelerator Conference
Albuquerque, NM

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

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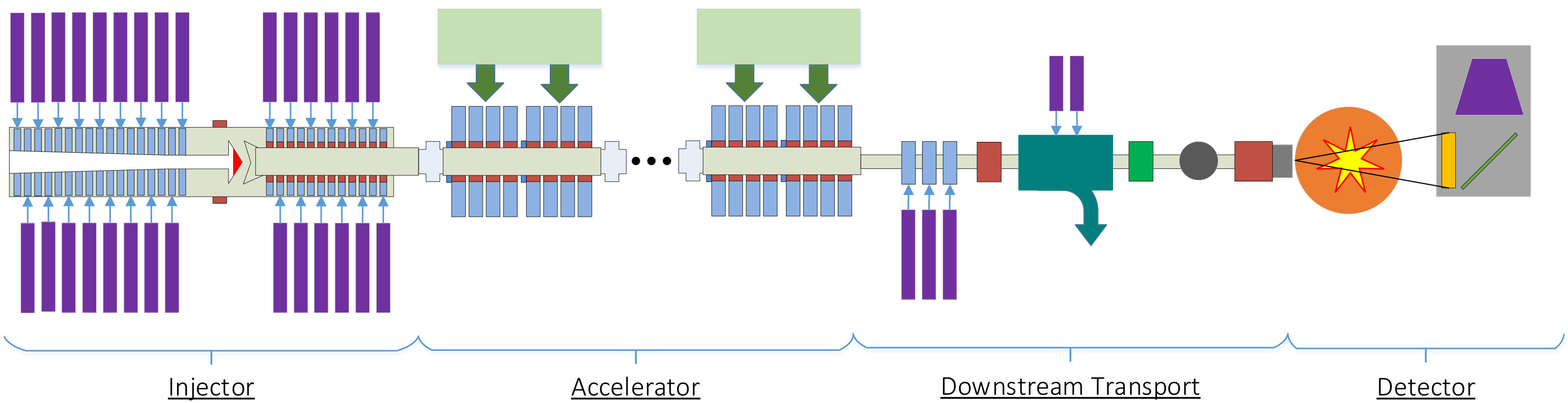
What is ASD-Scorpius?

- Four-pulse, Single-axis Radiographic System which is part of the Enhanced Capability for Subcritical Experiments (ECSE) Program
  - Includes both the source and the detector
  - Image quality equal to DARHT-1
  - Pulse separation as short as 200 ns (center to center)



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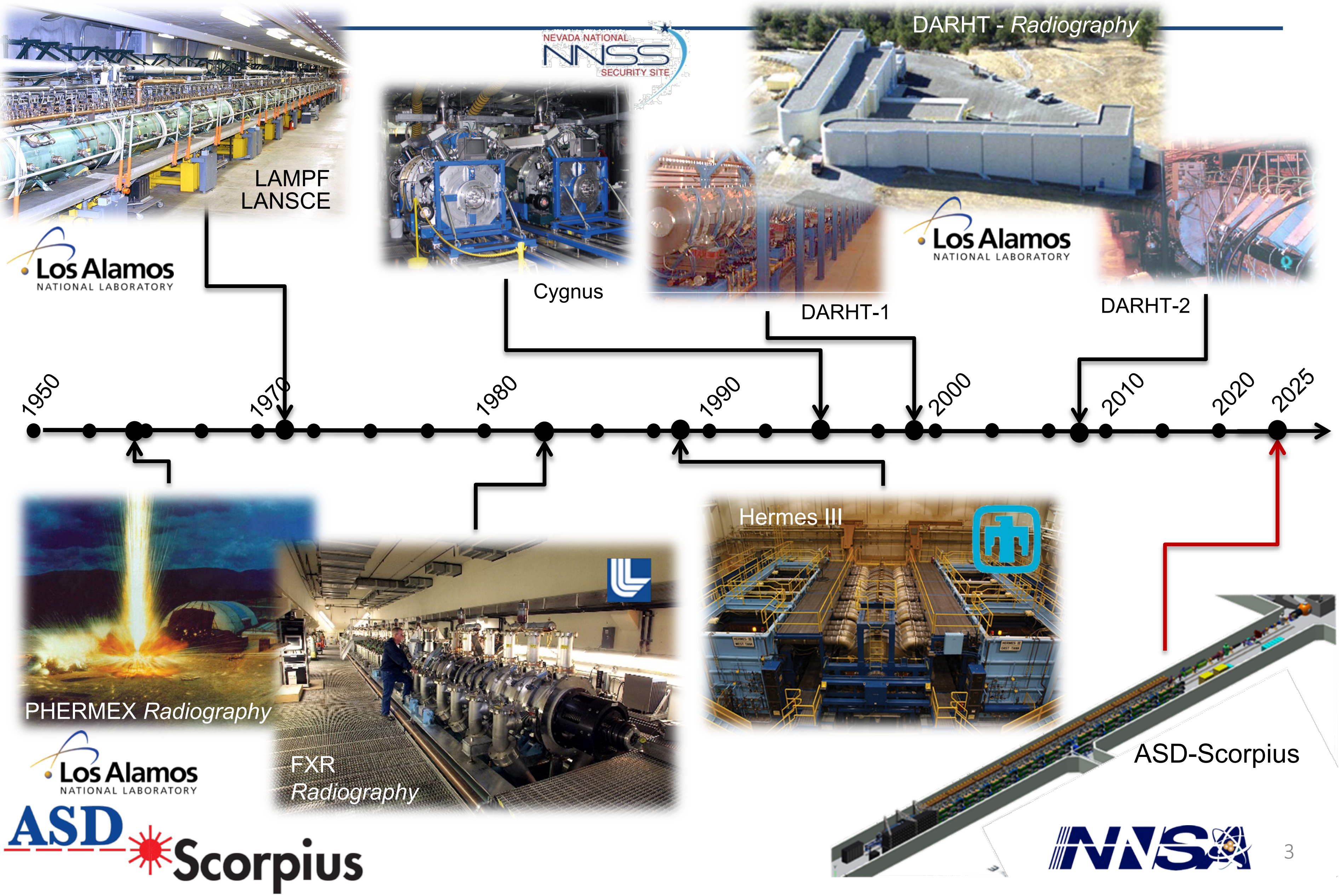
ASD-Scorpius is based on a long history of radiographic systems, accelerators, and pulsed power machines.



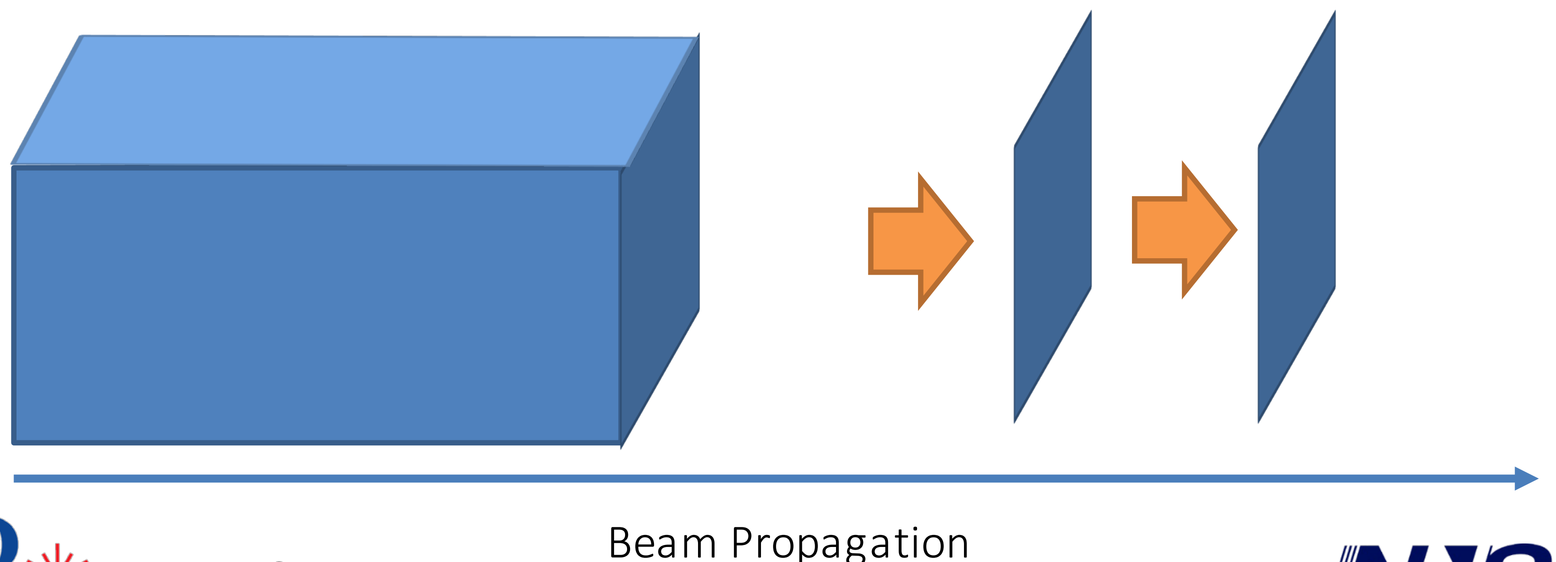
Geometries used in Warp for simulating Scorpius Beamline

3D-XYZ/2D-RZ

- Used in AK gap where electron source (cathode) and entrance to beampipe.
- Axial (Z) electric fields required to compute space charge limited electron emission.
- 3D needed when symmetry is broken. (e.g. solenoid misalignments/dipole fields)

2D-XY Slice

- Once electron beam is relativistic, a slice approximation works well as the beam stretches on axis in the bema frame and axial density gradients are not as important.
- Can assume particles are infinite in extent in z and advance particles from slice to slice along accelerator.



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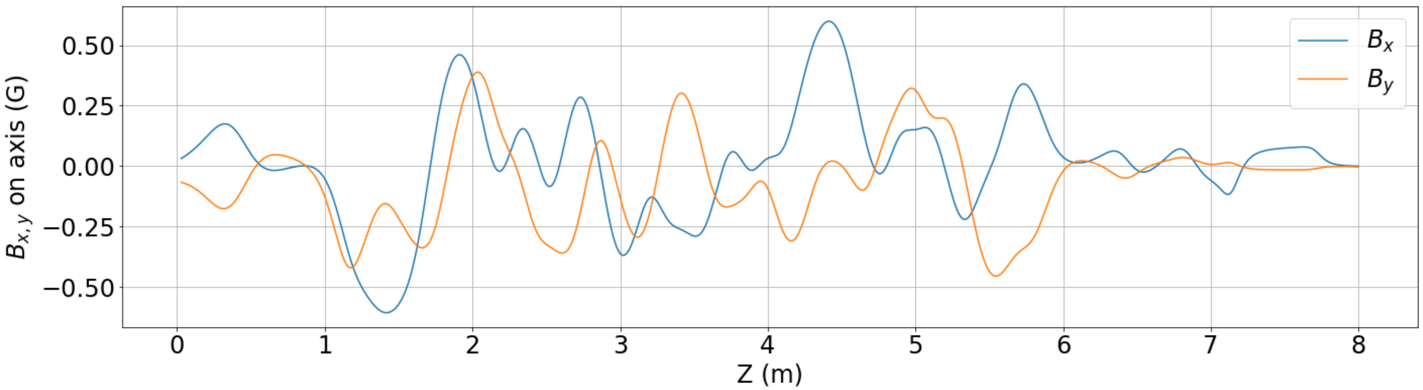
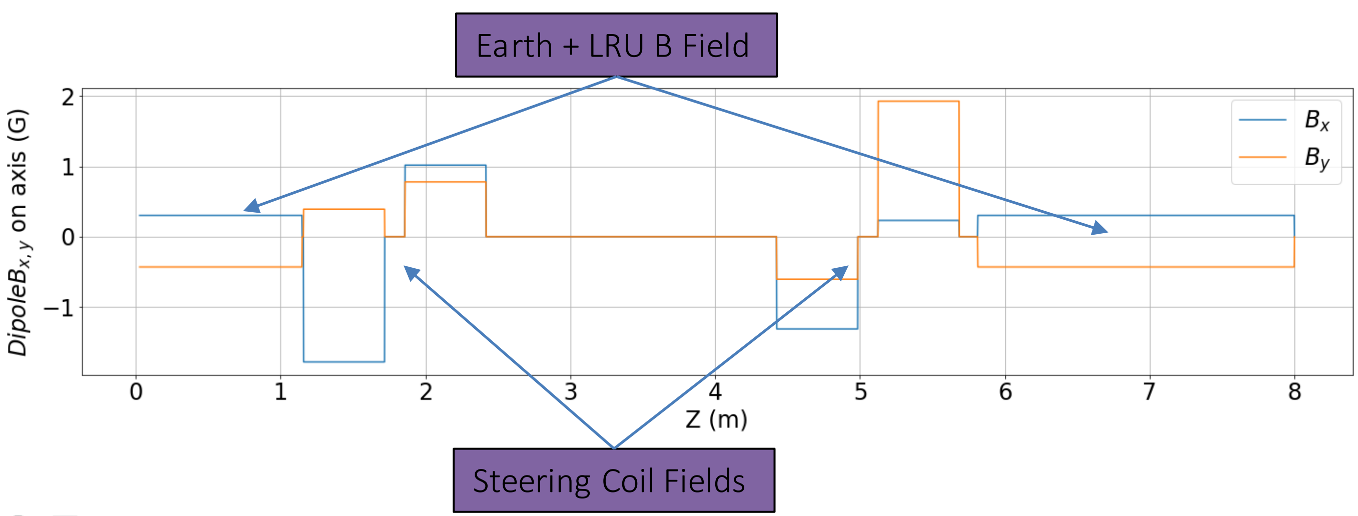
3D Simulations of injector including error and stray B fields





- Errors due to misalignments of anode beampipe, cathode, and solenoids in injector.
- Worst case alignment, not accounting for homogenizer rings.
- Stray fields as well as steering fields included in this figure.
- Assumption: Metglas in IVA cells shields stray fields.

Cathode/Anode offsets	0.5 mm
Bucking/Focus magnet offsets	0.2 mm
Bucking/Focus magnet rotational alignment error	0.5 mrad
IVA magnet offsets	0.5 mm
IVA magnet rotational alignment error	10 mrad

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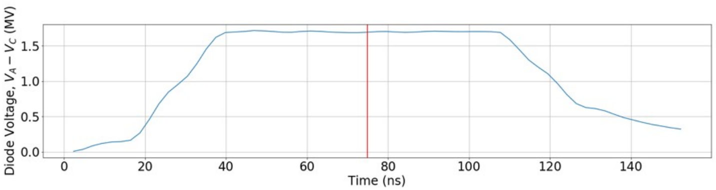
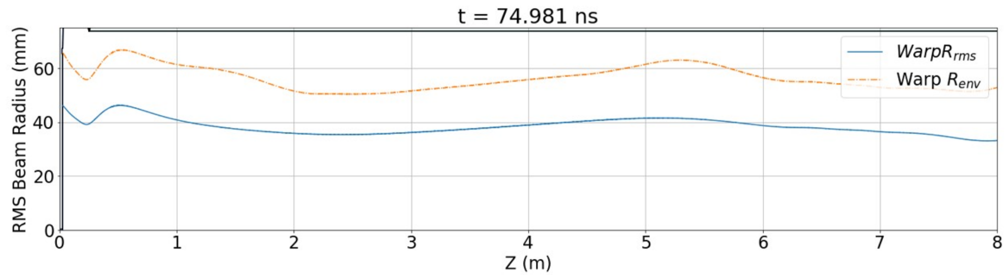
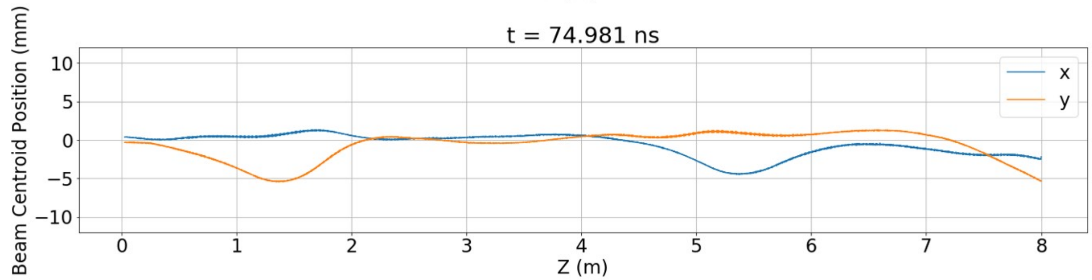
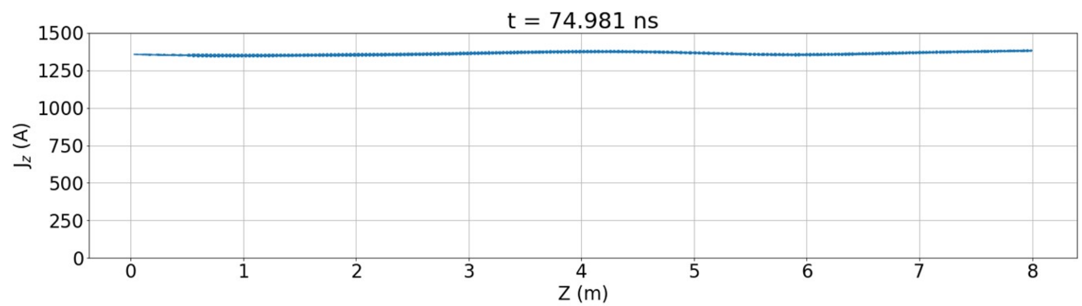
Nominal Tune at 1.7 MV with errors and steering



- *The beam can be steered back onto axis well within the margins of the steering coils.*
  - *Max coil field ~ 2 G, can operate up to 5 G.*
- *The beam does not scrape on the tip of the anode beampipe.*
- *R_{env} is the centroid radius plus envelope radius.*

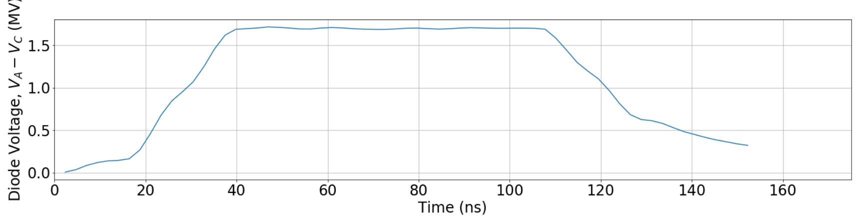


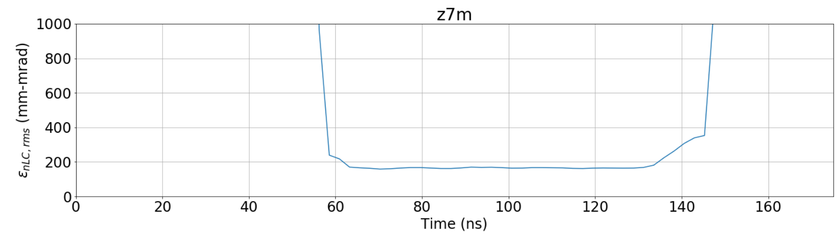


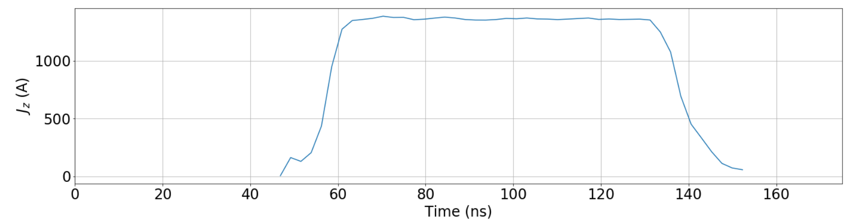


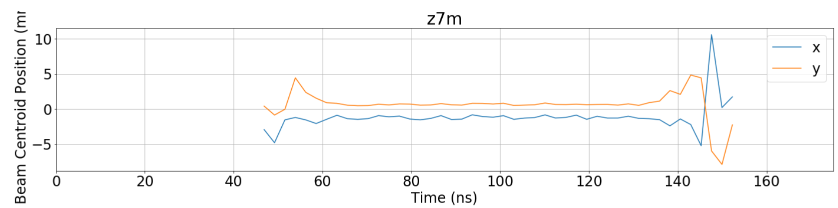
Beam Parameters at Injector Exit (7 m)

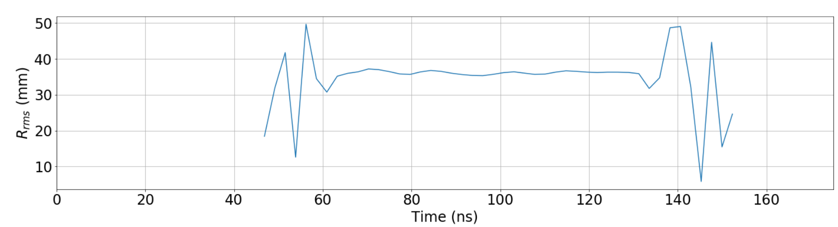
- Beam parameters at the exit meet requirements in the flat top.
- Voltage Rise time meets ~ 20 ns requirement
- Current Rise time at exit of the injector after scraping is ~ 10 ns.
- Emittance during flat top meets requirements.



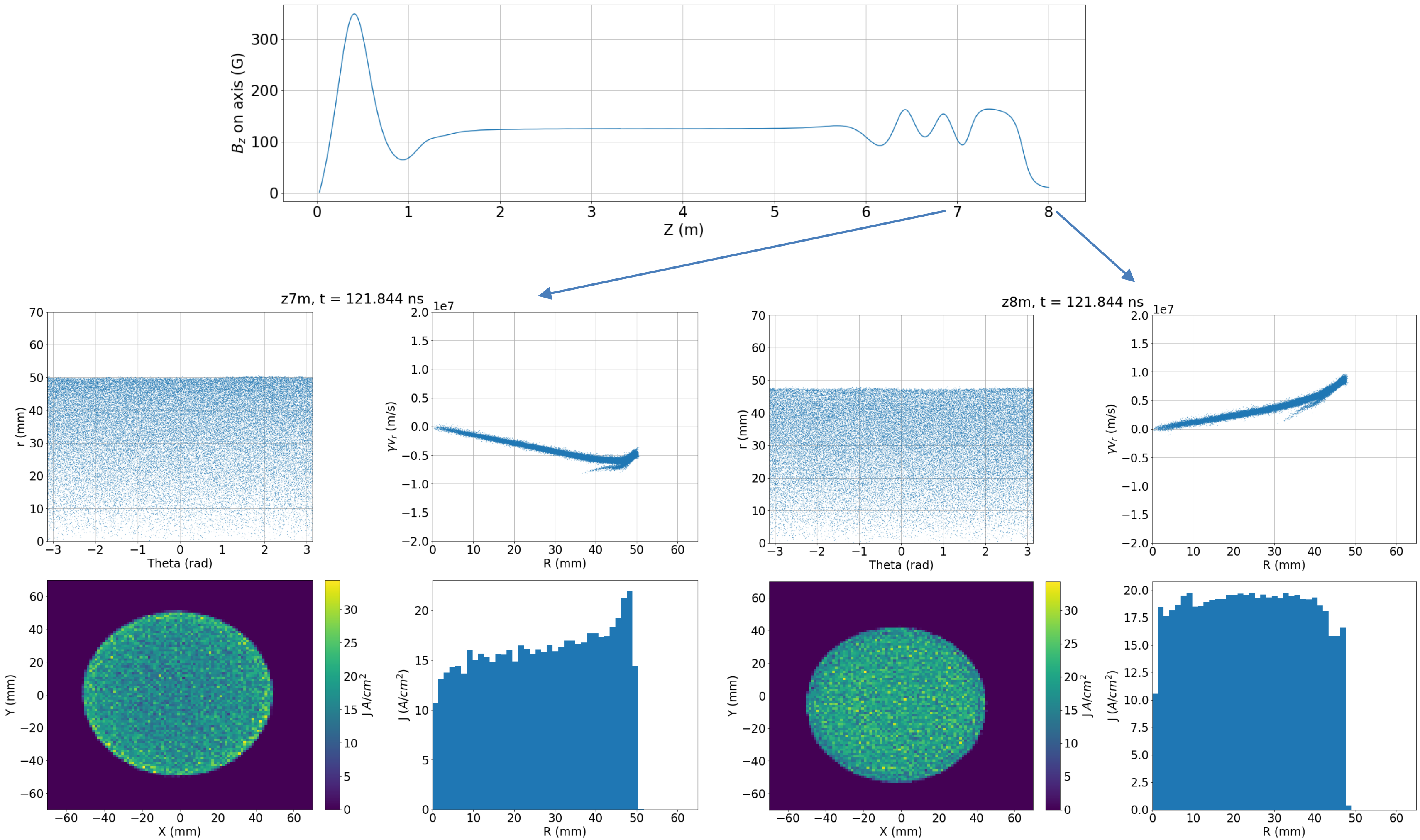




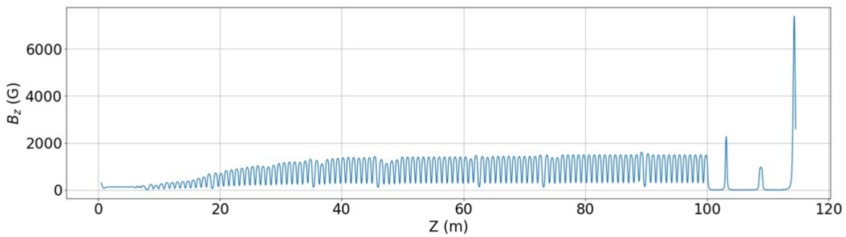


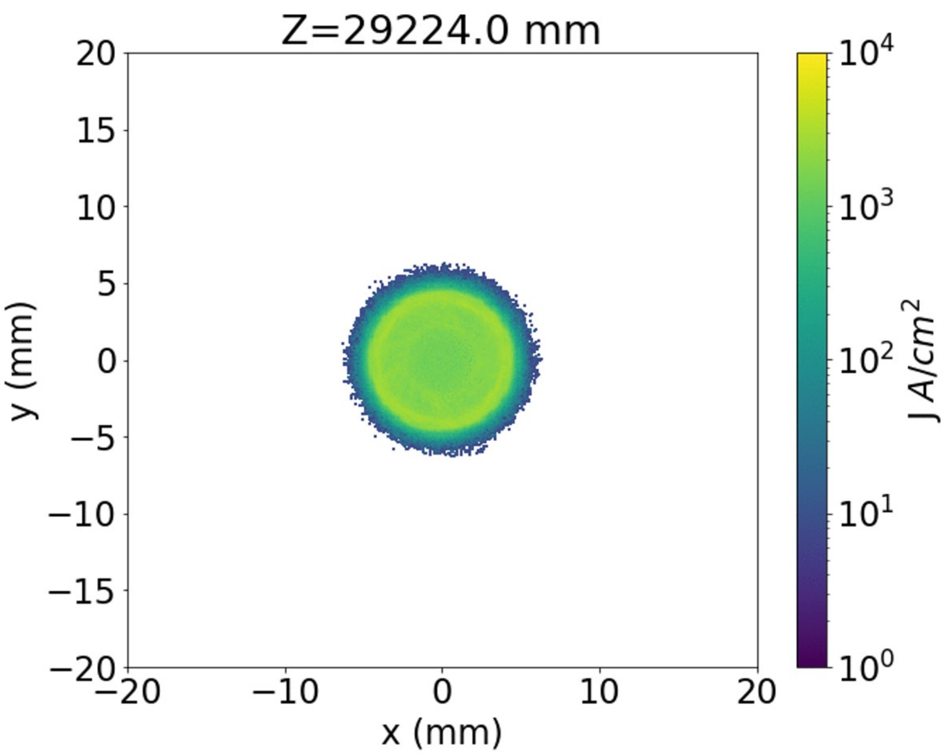


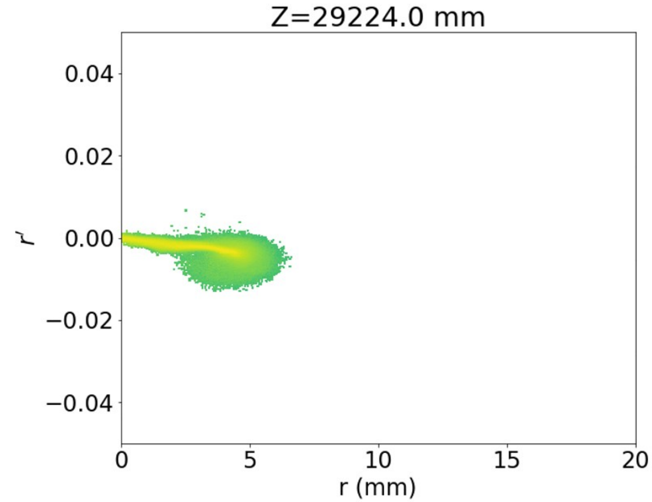
Spatial Uniformity of Beam at injector exit (7 m) and accelerator entrance (8 m)

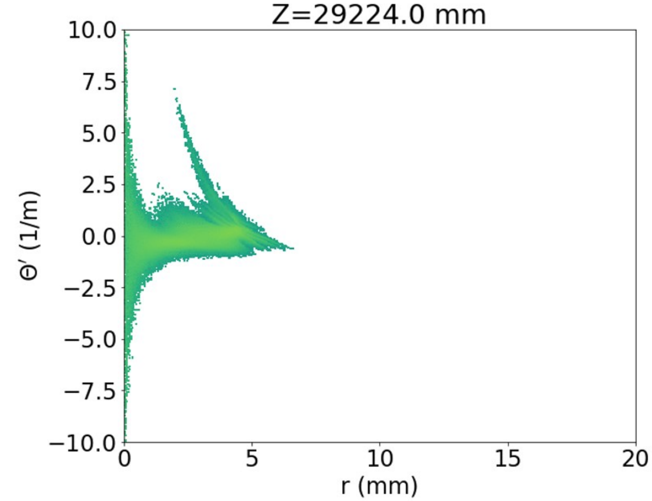


Some azimuthal mode structure is present in beam when propagating through accelerator with 2D slice PIC code in WARP









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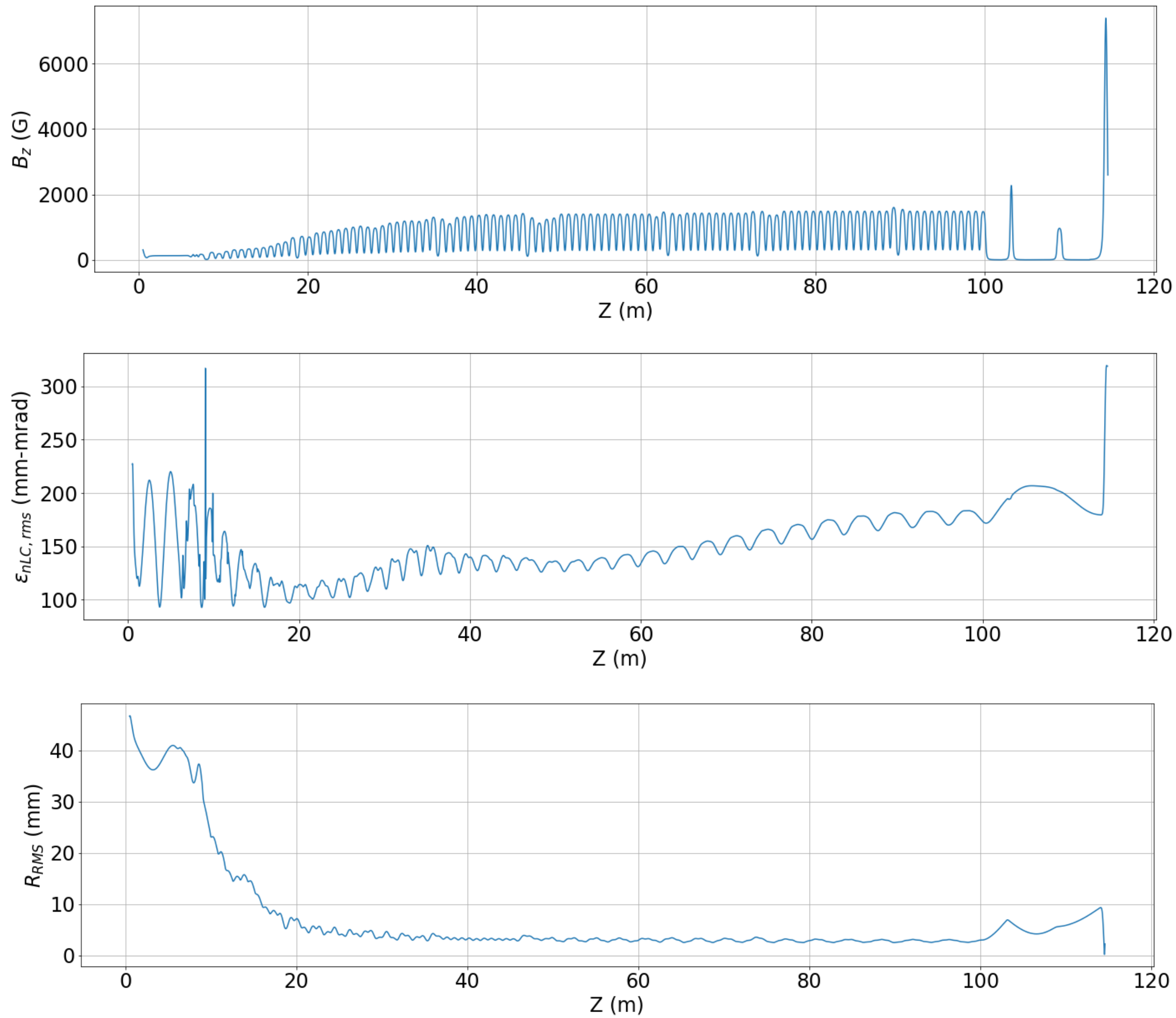
Beam emittance growth is tolerable

- Emittance growth due to azimuthal mode growth is tolerable through accelerator given nominal tune.
- Structure may lead to hot spots in radiography, though DST, target effects, and time averaging the beam are not currently being modelled.
- LSP and AMBER simulations with 1D slice PIC show constant emittance.



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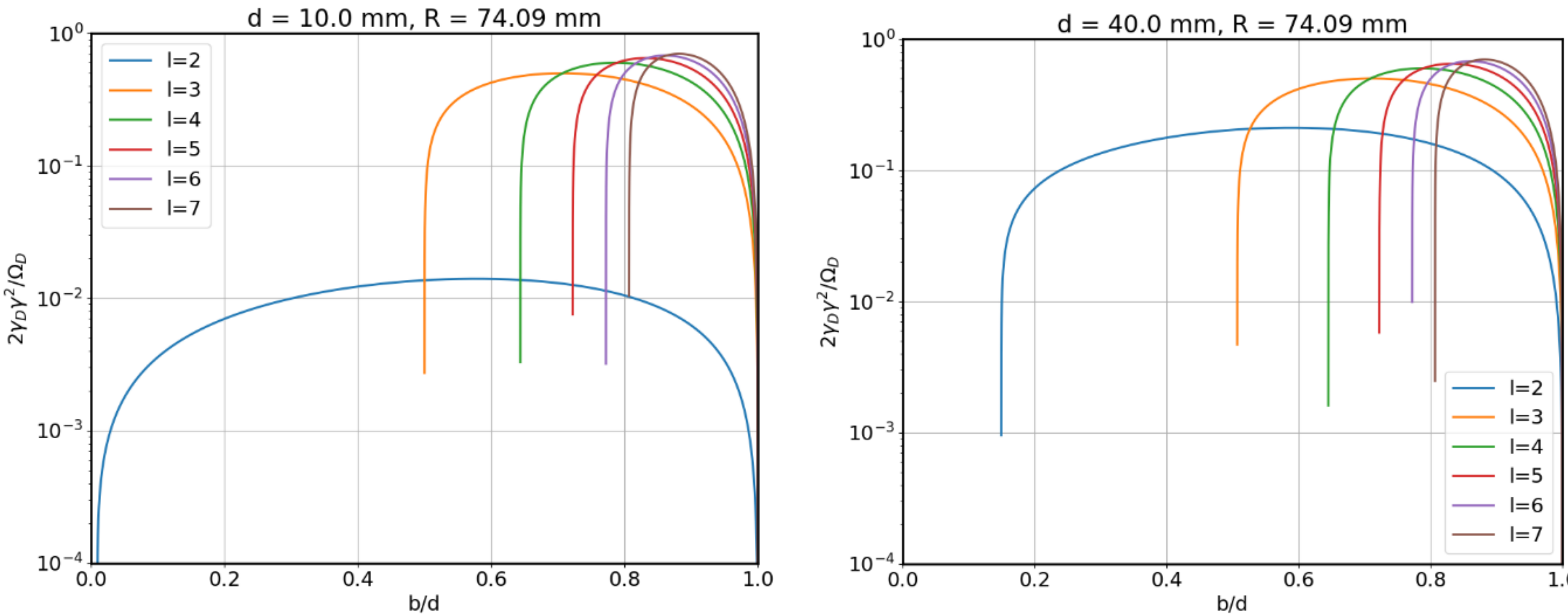
Analytical Diocotron Growth Rate



$$\gamma_D(l) = \frac{\Omega_D}{2\gamma^2}\left\{4\left(\frac{b}{d}\right)^{2l}\left[1 - l\left(1 - \left(\frac{b}{d}\right)^2\right)\left(\frac{d}{R}\right)^{2l}\right] - \left[2 - l\left(1 - \left(\frac{b}{d}\right)^2\right) - \left(\frac{d}{R}\right)^{2l}\left(1 - \left(\frac{b}{d}\right)^{2l}\right)\right]^2\right\}^{\frac{1}{2}}$$

Jo, Y. H., Kim, J. S., Stancari, G., Chung, M. & Lee, H. J. Control of the diocotron instability of a hollow electron beam with periodic dipole magnets. *Phys. Plasmas* **25**, 011607 (2018).

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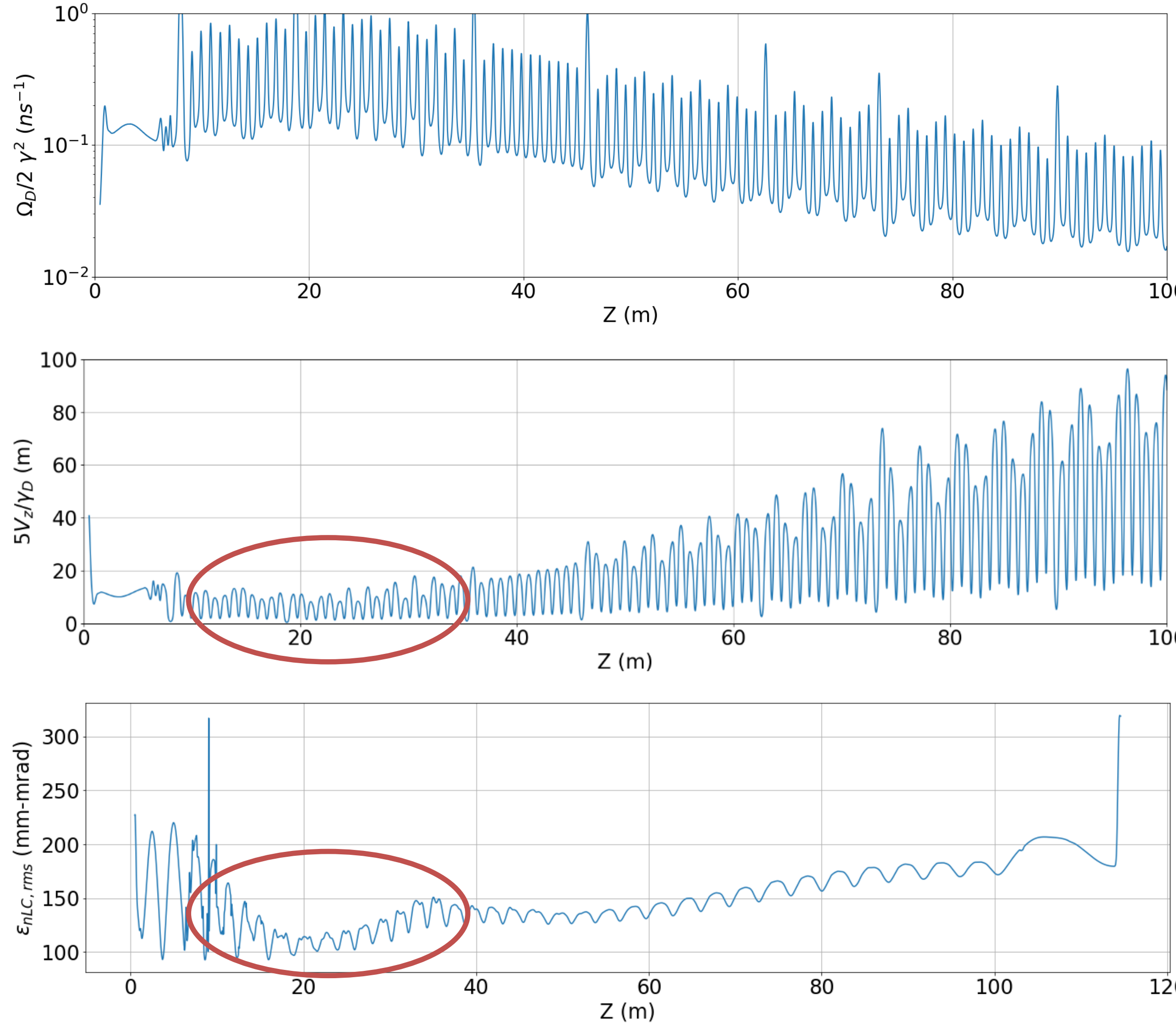
Calculated Growth Rate and Length in Scorpius

- Calculated distance through accelerator to see emittance growth matches well with 5 e-folds.
- Saturation of the diocotron growth does not lead to large emittance increases.
- Could lead to hot spots in radiography.
- Lower



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Summary

- Scorpius Injector has been modelled in Warp 3D and evaluated against engineering tolerances to determine that beam quality delivered from injector is predicted to meet radiographic requirements.
- Azimuthal mode growth from slightly hollow profile does not lead to excessive emittance growth when propagating through accelerator.